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Valley blockade in a silicon double quantum dot

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Electrical transport in double quantum dots (DQDs) illuminates many interesting features of the dots' carrier states. Recent advances in silicon quantum information technologies have renewed interest in the valley states of electrons confined in silicon. Here we show measurements of dc transport through a mesa-etched silicon double quantum dot. Comparing bias triangles (i.e., regions of allowed current in DQDs) at positive and negative bias voltages we find a systematic asymmetry in the size of the bias triangles at the two bias polarities. Asymmetries of this nature are associated with blocked tunneling events due to the occupation of a metastable state. Several features of our data lead us to conclude that the states involved are not simple spin states. Rather, we develop a model based on selective filling of valley states in the DQD that is consistent with all of the qualitative features of our data.

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I. INTRODUCTION

The conduction band of an indirect semiconductor has multiple degenerate minima. Silicon, for example, has six equivalent minima (or valleys) at wave vectors 85% of the way to the zone boundary in the equivalent [100] directions. This means conduction electrons have an additional degree of freedom when compared to those in direct gap semiconductors (with conduction band minima centered at k = 0). Although some implications of this valley degree of freedom were measured as far back as 1966 in Shubnikov-de Haas oscillations [1], there has been a recent spike in the amount of work focusing on the valley properties of conduction electrons in silicon. This includes measurements of valley splittings in different Si-based quantum dots [2-8]. Much of the impetus behind this interest is due to recent developments in solid-state quantum computation. These developments have highlighted several ways in which the valley state of conduction electrons can influence the quantum behavior of confined electrons. This includes valley-induced oscillations of the exchange interaction over atomic length scales [9], and spin relaxation hot spots [5]. Valley states are also believed to influence the voltage-induced g-factor shift of a quantum dot spin [10], which enables spin qubit addressability [11]. Furthermore, when creating an electron spin qubit one needs two isolated spin states; thus it is beneficial for the lowest-lying valley states to be separated by an energy larger than the Zeeman splitting of the spin states.

In this paper, we report transport measurements of a silicon double quantum dot that reveal a rectification effect between bias voltage polarities. To explain our data we propose a model involving the valley degree of freedom and a substantial difference in the electron filling of the two quantum dots. The model suggests that this type of blockade could be used to probe several aspects of valley physics similar to how Pauli spin blockade (PSB) has been used to probe solid-state spin physics.

II. RESULTS AND ANALYSIS

Our device [see Fig. 1(a)] consists of a mesa-etched silicon nanowire formed from a (100) silicon-on-insulator substrate [12]. A SiO₂ dielectric layer separates three polysilicon finger gates from the nanowire. These gates, spaced 40 nm edge-to-edge, conformally coat the nanowire and are used to electrostatically create tunnel barriers. A second SiO₂ dielectric layer electrically isolates the finger gates from a polysilicon global upper gate, which is used to turn on conduction in the device. Far from the active device area shown, ohmic contacts are formed on degenerately doped regions of the mesa-etched silicon. In addition to forming the barriers between the quantum dots and the leads, the outermost finger gates also serve as plunger gates, raising and lowering the chemical potentials of the quantum dots.

Figure 1(b) shows dc transport measured in our device as a function of the voltages on the outer two finger gates, V_{LGD} and V_{LGS} . All data presented are taken in a dilution refrigerator at a nominal base temperature of 45 mK. The measurement results in a honeycomb stability diagram where each cell of the honeycomb corresponds to a constant number of electrons on each dot [13]. At the corners of each hexagonal cell are regions, called bias triangles, where a tunneling current is energetically favorable. Since the applied source-drain bias voltage, V_b , determines the energy window between the Fermi levels of the two leads, one expects that, for standard Coulomb blockade (i.e., in the absence of spin or valley effects), the size of the bias triangles to be proportional to $|V_b|$ Ref. [13], and

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FIG. 1. Charge stability diagram. (a) Scanning electron micrograph of a device similar to the one measured. Current is measured at the source lead with the bias voltage applied to the drain. Not shown is a global upper gate used to turn on conduction in the silicon. (b) dc transport through our double quantum dot measured with $V_b = 1.5$ mV, an upper gate voltage of $V_{\text{UG}} = 3.5$ V, and a center lower gate voltage of $V_{\text{LGC}} = -1.733$ V. This measurement spans five charge transitions on the source side dot and three on the drain side dot. At lower V_{LGS} and V_{LGD} values our noise floor of ± 0.1 pA prevents precise measurement of bias triangle sizes due to the low current values, while at higher values the bias triangles are not very well formed as cotunneling effects begin to become evident. All voltages are referenced to ground and the apparent background current is a result of an offset in the current preamplifier.

that the polarity of the bias should not change the size of the triangles.

Data taken on a finer scale focusing on a single set of bias triangles is shown in Fig. 2(a) taken with $V_b = 1.5$ mV and in Fig. 2(b) with $V_b = -1.5$ mV. There is a clear asymmetry in the size of the triangles for the two polarities contradicting the expectation that the polarity of V_b would not affect the triangle size.

To quantify the size of the triangles we use the width of the triangles in V_{LGD} , which we call V_{open} (indicated by the black arrows in Fig. 2). As shown in Fig. 3, the size of the triangles does scale linearly with $|V_b|$ for both positive and negative biases.¹ Furthermore, the size difference between the two bias polarities is constant across a wide range of $|V_b|$. V_{open} corresponds to the change in V_{LGD} that shifts the chemical



FIG. 2. Size asymmetry. A finer measurement of the bias triangles from column 2 and row 2 in Fig. 1. (a) Measured with $V_b = 1.5$ mV, (b) measured with $V_b = -1.5$ mV. The size asymmetry of the triangles can be quantified by ΔE_{open} calculated using the V_{open} values indicated by the black arrows. Similar asymmetries were observed in the majority of charge transitions pictured in Fig. 1; a mild shift in charge offset over some months is reflected in a small position shift (about 0.02 V) with respect to the same triangle in Fig. 1(b).

potential of the drain dot across the energy window where conduction is allowed. In a typical nonblockaded situation this window corresponds to the bias window $e|V_b|$. In all our measurements showing a size asymmetry the positively biased triangles were larger than the negatively biased triangles. Thus, we assume the positive biased triangles correspond to a nonblockaded situation allowing us to define a lever arm in the same manner described in Ref. [13]

$$\alpha = \frac{e|V_b|}{V_{\text{open}}|_{V_b>0}},\tag{1}$$

with *e* being the electron charge. This α converts V_{open} to an energy $E_{\text{open}} = \alpha V_{\text{open}}$. The asymmetry can then be quantified in units of energy by

$$\Delta E_{\text{open}} = e|V_b| - \alpha V_{\text{open}}|_{V_b < 0}.$$
 (2)

Size asymmetries of this nature are typically associated with current rectification due to a metastable excited state of the electrons on the DQD. The most common example is PSB [14–24], where the occupation of a spin triplet state

¹One expects the trend in this figure to intercept the origin, which it does not. We were unable to confirm a specific source of this.



FIG. 3. Triangle size vs. bias voltage. Bias triangle size increases linearly with the magnitude of the bias voltage V_b . The slopes from the $V_b > 0$ and $V_b < 0$ polarities are 7.7 and 7.9, respectively. The asymmetry observed in Fig. 2 is consistent at all $|V_b|$ investigated.

in the (1,1) charge configuration prevents current flow that would otherwise be allowed through the ground singlet states.² Comparisons between our data and qualitative expectations of PSB reveals several inconsistent features. First, the size asymmetry of Fig. 2 exists at nearly all the transitions shown in Fig. 1 whereas PSB, generically being an odd-even filling effect, is expected in, at most, 1/2 of the transitions.³ Second, all of the asymmetries observed had the same polarity (larger triangles measured with $V_b > 0$). Both of these observations are shown in Fig. 5, which has the values of ΔE_{open} for all 15 transitions shown in Fig. 1. In contrast, PSB is expected to

²In the usual PSB model the electron occupations of the dots are considered to be effectively (1,1) and (0,2), with any other electrons on the dot forming closed shells in lower orbits and thus inert. Throughout this paper when we reference the (1,1) and (0,2) charge states we are referring to effective charge states like these.

³PSB in silicon has been reported with unusual fillings, most notably in Ref. [17]. These unusual electron fillings are typically explained using the valley degree of freedom in silicon, which allows for higher spin state formation [30], which could allow spin blockade to occur at consecutive transitions. show size asymmetries with alternating polarity as one moves through the honeycomb [15]. Third, as shown in Fig. 4, our data does not have a systematic trend with respect to magnetic field B_0 applied perpendicular to the substrate. Although the magnetic field does change the magnitude of the size asymmetry the dependence is not what is expected from simple spin states as one might expect with PSB. In PSB, one expects a systematic change in the size of the bias triangles due to two effects. (i) The exchange energy can have a magnetic field dependence [15], and (ii) the energies of the polarized spin triplet states have a magnetic field dependence due to the Zeeman effect [16,25]. Fourth, as shown in Fig. 5, our data show a systematic dependence on V_{LGS} that is unexpected for the case of PSB. Although changing the voltage applied to a barrier gate can change the magnitude of the exchange energy [19], the effect is too small to be a plausible explanation for the trend we observe.

III. MODEL AND DISCUSSION

The inconsistencies between our data and traditional PSB model lead us to believe the asymmetries in our bias triangles are not due to simple spin states; therefore, another degree of freedom must contribute to the rectification. We developed a model of blockade that centers on the valley degree of freedom of electrons in silicon. In our model, we assume all the conduction electrons in the DQD occupy one of two valley states, v_+ and v_- . However, the relatively large size and electron occupation of our dots results in bands of states for each valley type (Fig. 6). The bottom of the bands of each type are separated by the valley splitting Δ_v , which depends primarily on the surface potential experienced by the electrons [26]. The splittings between successive levels in the individual bands are predominantly determined by the orbital spacing E_{orb} .

Figure 6 shows the details of this model in the simplified constant interaction picture, where we have suppressed the charging energy to evoke the idea of bands, appropriate near the triple points of the honeycomb. In the limit of empty dots the ground-state chemical potential is the same for both dots. This situation results in typical bias triangles with no asymmetry. However, by adding electrons to one of the dots we fill the lower-lying valley states. At some number, N_B , all the ν_+ states below the bottom of the ν_- band will be filled and the chemical potential for the two valley types will be degenerate on that dot. With M, the number of electrons on



FIG. 4. Magnetic field dependence. Size asymmetry as a function of applied magnetic field for the first three rows of transitions shown in Fig. 1. (a) Column 1, (b) column 2, and (c) column 3. Although the magnetic field clearly changes the magnitude of the size asymmetry, we do not see a clean systematic dependence as one would expect from spin states.



FIG. 5. Gate dependence. Dependence of ΔE_{open} on V_{LGS} for each column of the honeycomb in Fig. 1. Each data point shown is an average of all the ΔE_{open} determinations for a given transition. Some of these averages include data taken with source and drain connections reversed as a check against any extrinsic voltage offsets. There is a general trend of decreasing ΔE_{open} as the source dot is successively filled. This trend comes about naturally in the valley band model (see text).

the other dot, being less than N_B the chemical potentials for the two valley types are split on the second dot. This situation, one dot with degenerate chemical potentials for the two valley types and one with split chemical potentials, allows for a blockade to occur in qualitative agreement with our data: An electron loads into a v_- state on the first dot only to become trapped since the interdot tunneling event is energetically unfavorable for v_- states. Thus, current is blocked until some valley relaxation or intervalley tunneling event occurs.⁴ This situation is shown in Fig. 6(b) for $(N > N_b, M = 0)$ and

⁴This argument assumes that current cannot flow by creating a hole in the other valley state on the left dot; however, we expect this process to be suppressed because the state with an intervalley electron-hole Fig. 6(d) for $(N > N_B, N_B > M > 0)$. However, when the bias is reversed, the second dot in the conduction path now has degenerate chemical potentials for the two valley types and no blockade occurs [see Fig. 6(c)]. As with PSB, this blockade results in a bias triangle size asymmetry ΔE_{open} . The magnitude of ΔE_{open} corresponds to E_{block} , the energy splitting between the lowest unoccupied ν_- state and the highest occupied ν_+ state on the second dot. E_{block} can be reduced by adding electrons to the blocking dot and successively filling the lower-energy valley band as shown in Fig. 6(d).

Applying this model to our system we see it predicts a blockade that is in qualitative agreement with our data. A drain-side dot filled such that $N > N_B$ and a source-side dot in the $N_B > M > 0$ regime would lead to the size asymmetry we observe, specifically, (i) a blockade for multiple successive transitions and (ii) the same polarity of size asymmetry for these transitions. Furthermore, the magnetic field dependence of the bias triangle size would depend heavily on the details of the states that make up the bands, and is by no means expected to be systematic or monotonic. Finally, adding electrons to the source-side dot would reduce E_{block} and therefore reduce ΔE_{open} . In our data this would correspond to moving vertically through the honeycomb in Fig. 1 and results in the reduction in ΔE_{open} seen in Fig. 5.

It is worth noting that this model also predicts other situations where a blockade is expected to occur. For instance, in the regime $0 < N < N_B$ and M = 0 the splitting between chemical potentials of the two valley types is different for the two dots, allowing for a situation where the interdot tunneling for an electron in a v_- state is energetically unfavorable even though interdot tunneling for the v_+ electrons would be favored. In this situation the blockade region of a bias triangle would not span the entire base of the triangle resulting in regions of allowed current that are not triangular in shape but have tails similar to those observed with lifetime enhanced

pair on the left dot is an excited state of the dot, which will be gapped from the ground state due to finite-size effects.



FIG. 6. Model. Our model in the simplified constant interaction picture. We have suppressed the charging energy to evoke the idea of bands. (a) Red and blue levels correspond to v_+ and v_- valley types, respectively. When the dots are empty (0,0), the ground states in each dot are the same valley type, and the splitting to the lowest state in the opposite valley is also equal. This results in no blockade, and bias triangles with size determined by $|V_b|$. (b) Filling the first dot with $N > N_B$ electrons removes the splitting between the chemical potentials of the two valley types. Blockade will occur when these degenerate levels lie between the ground v_+ and v_- states of the second dot, resulting in a bias triangle size asymmetry corresponding to ΔE_{block} . (c) Reversing the bias polarity in this situation results in fully formed bias triangles with no blockade. Whenever the interdot tunneling is favorable for the lower v_+ states the same is true for the v_- states. (d) Adding M electrons to the second dot reduces E_{block} , and thus the size asymmetry, by filling v_+ states and bringing the v_+ chemical potential closer to that of v_- leading to the dependence seen in Fig. 5.

transport [18,20] and predicted in high-field Pauli-spin blockade [25]. Also, in this model, the region of blocked current would grow as N increased from 0 to N_B . When $N \ge N_B$ the region of blockade would be maximized corresponding to an energy of Δ_v and the regions of allowed current would return to a triangular shape. The lack of a systematic increase in blockade size as we increase N in our data implies we must be in the $N > N_B$ regime. Finally, by switching the occupations of the two dots, $N \leftrightarrow M$, in any of the regimes should reverse the polarity of the blockade. The lack of independent plunger gates on our device prevents us from exploring these regimes.

A crucial assumption in our model is that the valley degree of freedom is a good quantum number; the symmetric and antisymmetric valley states represented in Fig. 6 are eigenstates of the combined Si band structure/interface, and in the absence of large interface roughness [27], the valley states represent a good quantum number. Furthermore, for the model to apply several things must be true. First, there must be low intervalley tunneling rates. Furthermore, the z orbital spacing E_z , where z is the direction perpendicular to the substrate, must be large relative to both Δ_v and the lateral orbital spacing $E_{\rm orb}$. If this were not the case, adding electrons to one of the dots would cause significant changes to the z dependence of the wave function, which would distort the relative valley states on each dot, leading to intervalley tunneling. This requirement seems probable in our device where the lithographic distance between barrier gates is 40 nm, while a typical thickness for a silicon MOSFET inversion layer is roughly a tenth of that. In addition to the restriction on E_z , the lateral orbital spacing must be small relative to Δ_v for the bandlike picture to be accurate.

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Using a constant interaction picture and applying this model to our data we can extract certain energies. The largest splitting in Fig. 5 of ~0.6 meV gives a lower bound on Δ_v . This value is in the range of 0.1–0.8 meV reported by Refs. [5,28]. The slope of Fig. 5 implies a lateral orbital splitting $E_{\text{lat}} \sim 0.1$ meV. Furthermore, the noise level in our experiment of ± 0.1 pA implies a valley lifetime of $T_{1,v} \ge 1\mu$ s.

IV. FUTURE DIRECTIONS

The model we have described, although consistent with our data, needs to be verified with future measurements. Devices with extended functionality will allow for more quantitative comparisons between the model and experiment. Specifically, independent plunger gates for each of the dots as well as an ancillary dot for charge sensing would allow for the exact electron fillings to be determined. This ability would allow one to confirm the differences in electron occupation and examine other regions of the charge stability diagram where the model predicts the same type of blockade but in the opposite direction. Charge sensing would allow for a much wider range of state lifetimes to be probed. In addition to verifying the model, this would open the door to investigations of the coupling and relaxation mechanisms [29].

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